Sensing Task Allocation for Heterogeneous Channels in Cooperative Spectrum Sensing

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Abstract. *In the traditional centralized cooperative spectrum sensing, all secondary users sense the same channel. But, for a given channel, there exists detection performance diversity among all the users, due to the different signal-fading process. Involving the user with poor performance in cooperative sensing will not only deteriorate the detection correctness but also waste the sensing time. In the heterogeneous channels, the problem is even severe. A novel idea is to allocate the secondary users to sense different channels. We analyze the allocation problem before formulate it to be an optimization problem, which is a NP-hard problem. Then we propose the declined complexity algorithm in equal secondary user case and the two-hierarchy approach algorithm in unequal case. With the simulation, we verify the near optimality of the proposed algorithms and the advantage of the task allocation.*

Keywords

Cognitive radio, spectrum sensing, sensing task allocation.

1. Introduction

Cognitive radio (CR) [1] has been thought as the most promising technologies to solve the spectrum scarcity. It intelligently exploits the licensed spectrum resource to find the white (unoccupied) spectrum band to dynamically transmit the unlicensed signal. So the spectrum sensing is quite important to the cognitive users. Two correlative and incompatible requirements in the spectrum sensing are short sensing duration and perfect detection performance. Long sensing duration could gain more accurate detection performance to protect the primary users while leaves less time to transmit the secondary information. They two simultaneously affect the secondary throughput.

However, when it comes to the multiuser in the cognitive networks, the cooperation could relax the conflict, lying on the fact that increasing the detection performance not only depends on increasing the sensing duration but also depend on adding the number of the cooperative users. Considering the primary users may be several and they may use heterogeneous channels, how to efficiently allocate the cognitive users to sense them is an important problem in the cooperative networks. And here, we aim at maximizing the expected cooperative secondary throughput through assigning the secondary users to sense the multiple heterogeneous channels, i.e. the sensing task allocation.

The cooperative spectrum sensing (*CSS*) has received lots of attentions recently. About two types can be concluded: the first is like [2], [3], [4] whose secondary users are treated having the same signal-to-noise ratio (*SNR*), and the other is like [5] whose secondary users have different received SNR. This different received SNR is just one reason for our sensing task allocation. The other reason is the heterogeneity of different channel which will be explained latter. When the sensing task is mentioned, it means to sense one channel. The problem, which secondary user to sense which channel, is rarely studied. In [6], the author proposes two collaborative channel spectrum-sensing policies, namely, the random sensing policy and the negotiation-based sensing policy. Similarly, Allocated-group Sensing Policy (*ASP*) is proposed to identify the spectrum opportunities based on a dynamic ID numbering approach in [7]. And the secondary user in [8] randomly chooses *S* consecutive sub-bands to observe in the multiple-hypothesis-testing approach. But these sensing task allocations are all restricted to be spectral allocation, without spatial allocation. Mo Li adopts the Q-Learning method [9] to study the sensing task allocation, but its system model is distributed which is different from ours. In this paper we will investigate spectral and spatial allocation jointly, modeling as a matching problem between the secondary users and the heterogeneous channels.

In this paper, we consider a centralized CR network and explain the cooperative sensing process with the task allocation. Through the analysis of the detection performance of the cooperative sensing, we introduce the feasibility for sensing task allocation. Then the model is built. To solve it, we distinguish the equal and unequal secondary user case. Two near optimal algorithms are proposed correspondingly.

The rest of the paper is organized as follows: Section 2 presents the cooperative sensing system model. Section 3 is the problem formulation, and next is the two optimal algorithms. In Section 5, the near optimality of the proposed algorithms and the advantage of the task allocation are provided in. In the last section is the conclusion.

2. Cooperative Sensing System

2.1 System Model

Consider a centralized CR network consisting of M secondary users (denoted as SU_1, SU_2, …, SU_M) as depicted in Fig. 1. They are randomly distributed in the cognitive radio area. Also, we accept the fact that their movement is popular, such as mobile telephone, and the movement is considered in the system. At the same time, in order to coordinate the sensing and the access of multiple users, the secondary center is chosen here. It may be one fixed base station or mobile equipment, with responsibility for registering, collecting signals, fusing data, releasing commands and so on. Its coverage is shown in the figure, and the users out of the coverage are not in the range of sensing task allocation. It should be specially noted that the geographical position of all the secondary users as well as the primary users are known to the center through the GPS.

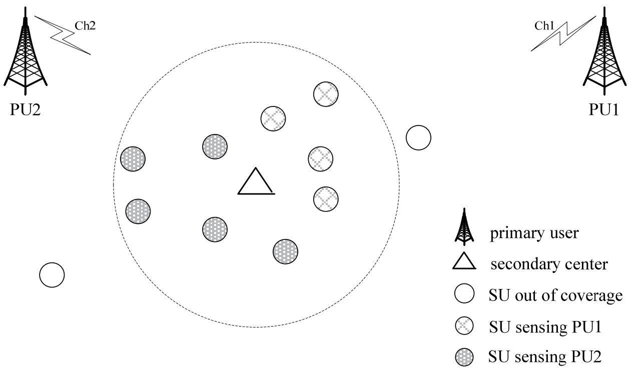

Fig. 1. An example of the system model.

Primary users, namely P_1, ..., P_U, such as the TV transmitters in WRAN 802.22 [10], sit around the cognitive radio area. Without loss of generality, we assume one primary user takes up one single channel, so sensing the channel is equal to sensing the primary user. We assume $U < M$, so that one sensing task could be done by cooperation of several users. For the secondary users, the target channels (experience large-scale fading) are heterogeneous, meaning that 1) they have different bandwidth B_k, $k = 1, 2,\ldots, U$, and 2) they have different average idle probability θ_k, $k = 1, 2,\ldots, U$. But these differences are not time-varying in our consideration, and can be probed aforehand, which is not in this paper's scope. In addition, the *CCC* (Common Control Channel) is a dedicated channel, and users access the CCC in a time-divided mode.

2.2 Cooperative Sensing Process Based on Sensing Task Allocation

Hardware limited, a secondary user can sense only one channel one time. If there are a number of channels to sense, i.e. a number of sensing tasks, it must sense them sequentially. In our study, we investigate the sensing task allocation in the case that one secondary user can only accomplish one task in one slot. How to allocate all the sensing tasks in a slot is our job in this paper.

A synchronous system is assumed, and time is divided into fixed-length slots. In each slot, seven phases are involved, shown in Fig. 2.

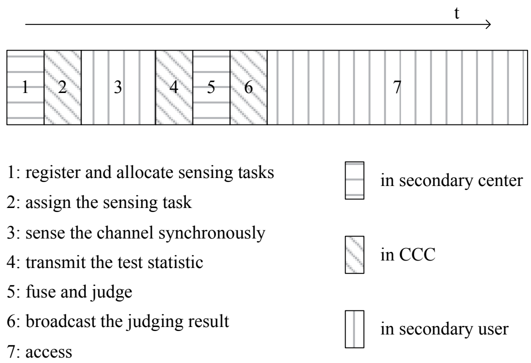

Fig. 2. The cooperative sensing process in one slot.

1) Register and allocate sensing task. From the system model, we can see one secondary user may move here and there, which makes the number and the position of the operating users changeable in different slots. Though it is reasonable to assume the invariability in one whole slot, the secondary center also registers the operating users repeatedly. Then it could estimate the average received SNR for every secondary user from the large-scale fading model. Using the SNR, it makes an appropriate plan of sensing task allocation.

2) Assign the sensing task. After the allocation plan is made, the secondary center assigns the sensing task, including the matches between the channels and the secondary users as well as the corresponding sensing duration.

3) Sense the channel synchronously. Once the secondary user obtains the sensing task, it starts to execute in energy detection. A channel may be sensed by several secondary users with the same sensing duration, different channel different sensing duration. So the duration of this phase affects the time for access, because of the constant slot. The rest of the paper will address the issue.

4) Transmit the test statistic. The soft information fusion [2] in next phase is adopted in the cooperative sensing, so in this phase, all the secondary users transmit the test statistic in time-divided mode of CCC. Note that the CCC is a dedicated channel so the report error can be ignored.

5) Fuse and judge. The secondary center fuses the received signal, and then makes the decision about whether the primary user occupies the channel or not.

6) Broadcast the judging result. Similar to phase 2.

7) Access. If the channel is detected to be idle, the secondary users sensing the channel will be allowed to access the channel in CSMA/CA, TDMA, OFDMA and so on. This phase determines the system throughput in this slot.

3. Problem Formulation

3.1 Feasibility of Sensing Task Allocation

In the introduction, we have explained the reasons for sensing task allocation: the different received SNR and the heterogeneity of different channel. The former is the user diversity, and the latter is the channel diversity. Because of the existence of the two diversities, we could match the users and the channels in an optimal scheme, to maximize the utilization of the spectrum resource. This is just the reason for the sensing task allocation. In addition, we will further clarify the feasibility for sensing task allocation in the view of the cooperative sensing.

We study the cooperative sensing in channel k. There are M_k secondary users assigned to sense channel k. And every user samples in a uniform sample speed f_s. Simply, we assume the noise's variance for every user is the same: $\sigma_1^2=\sigma_2^2=\ldots=\sigma_M^2=\sigma^2$. Energy detection and equal gain combination is used in the secondary center. Here we define the reported energy matrix as $\mathbf{u}^{U\times M}=[u_i^j]$, $i\le U$, $j\le M$ with the element defined as follows.

$$u_i^j=\sum_{l=0}^{N_i-1}\left|x_i^j(l)\right|^2 \tag{1}$$

where $x_i^j(l)$ is the received signal from the i^{th} primary user by the j^{th} sensing user with N_i samples. The test statistic u_i^j follows $N[E(u_i^j), Var(u_i^j)]$, which can be found in [5]. So the binary hypothesis test of PU_k is simplified as follows.

$$\begin{cases} H_k^0: & \sum_{i=1}^{M_k}u_k^{v_i}<\gamma_k \quad k=1,2,\ldots,U \\ H_k^1: & \sum_{i=1}^{M_k}u_k^{v_i}\ge\gamma_k \quad k=1,2,\ldots,U \end{cases} \tag{2}$$

where γ_k is the decision threshold for PU_k, and M_k is the number of the secondary users sensing the PU_k,

$$\sum_{k=1}^{U}M_k=M. \tag{3}$$

Then the performance of the cooperative spectrum sensing for PU_k can be evaluated as

$$P_{f,k}=Q\left(\frac{\gamma_k-N_kM_k\sigma^2}{\sqrt{2N_kM_k\sigma^4}}\right) \tag{4}$$

and

$$P_{d,k}=Q\left(\frac{\gamma_k-N_kM_k\sigma^2-N_k\sigma^2\sum_{i=1}^{M_k}\eta_k^{v_i}}{\sqrt{2N_kM_k\sigma^4+4N_k\sigma^4\sum_{i=1}^{M_k}\eta_k^{v_i}}}\right) \tag{5}$$

where v_i is the i^{th} secondary user of PU_k, and $\eta_k^{v_i}$ is the average local SNR at the v_i-th sensing user (the local SNR matrix:$\boldsymbol{\eta}^{U\times M}=[\eta_i^j]$, $i\le U$, $j\le M$). Fix the detection performance $P_{f,k}=P_{th1}$, $1-P_{d,k}=P_{th2}$, $k=1,2,\ldots,U$, where P_{th1} is the threshold of the false alarm probability and P_{th2} is the threshold of the miss detection probability. Then the threshold γ_k can be confirmed lying on the statistical characteristic of detection signal in channel k. Constitute (4) into (5), then we can obtain

$$P_{th2}=Q\left(\frac{Q^{-1}(P_{th1})\sqrt{2}-\sqrt{N_kM_k}\Gamma_k}{\sqrt{2+4\Gamma_k}}\right) \tag{6}$$

where $\Gamma_k=\frac{1}{M_k}\sum_{i=1}^{M_k}\eta_k^{v_i}$ is the average global SNR (it is different from the average local SNR, and they two are all estimated parameters.) for PU_k. From this expression (6), we can conclude that three parameters are changeable in the given detection performance, which are N^k, M^k and Γ^k.

From Fig. 3 (note: N is just the minimum number of samples, and it's a theoretic number to research the mutual relationship. More concrete discussion of N can be found in [12]), the increasing of the number of sensing users can weaken the acquirement of the sensing duration. But if all the users are to sense the same channel, the global SNR will decrease, making the sensing duration increase again. So, there exists a tradeoff for the user number in every channel, meanwhile, the fixed number of all the users forces another tradeoff among different channels. This characteristic paves the way for the sensing task allocation.

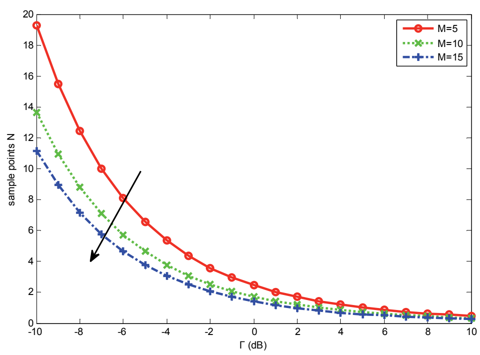

Fig. 3. The mutual impact among N, Γ and M ($P_{th1}=0.1$, $P_{th2}=0.1$).

3.2 Problem Formulation

We want to achieve optimal expected cooperative secondary throughput in a slot, while guarantee the interference to every primary user below a given ratio. Simply, the slot duration is fixed in the paper. From the cooperative sensing process, we know the time in a slot is divided into seven phases, and the time in phase 1,2,4,5,6 is fixed once the operative user is registered at the beginning of a slot. So we denote the residual time (the sensing and the access time) as T.

If the channel is idle and the cooperative sensing result is H_k^0, i.e. the probability to access the channel is $P(Access, idle) = (1 - P_{f,k})\theta_k$, then the cognitive radio sends its signal with unit power level. Considering the AWGN channel in the small-sized cognitive radio network, we define the bandwidth B_k as the channel capacity in channel k. In addition, the threshold of the interference ratio in all channels is supposed to be same: I_{th}. Then the problem is formulated as follows. Our main job here is to allocate the M secondary users to sense the U primary users.

$$\begin{aligned} &\max \quad Th(\vec{M},\vec{\Gamma}) = \sum_{k=1}^{U} B_k\theta_k(1-P_{f,k})(T-\tau_k) \\ &s.t. \begin{cases} (1-\theta_k)(1-P_{d,k}) < I_{th} \quad k = 1,2,...,U \\ \sum_{k=1}^{U} M_k = M \end{cases} \end{aligned} \tag{7}$$

where $\tau_k = N_k/f_s$ is the sensing duration for the k^{th} primary user, $\vec{M} = (M_1, M_2, ..., M_U)$ and $\vec{\Gamma} = (\Gamma_1, \Gamma_2, ..., \Gamma_U)$. Notice that the false alarm probability $P_{f,k}$ may be different in different channels, depending on the number of samples and cooperative users from (4). In order to reduce the complexity and give prominence to the sensing task allocation, we suppose the false alarm probability in all channels is the same: $P_{f,1} = P_{f,2} = \ldots = P_{f,U} = P_{th1}$. Further more, the least detection probability should guarantee the interference threshold. Then, the sensing duration for the k^{th} primary user can be denoted as follows by rewriting equation (6).

$$\tau_k = N_k / f_s = \left[\frac{Q^{-1}(P_{th1})\sqrt{2} - Q^{-1}\left(1 - \frac{I_{th}}{1-\theta_k}\right)\sqrt{2+4\Gamma_k}}{\sqrt{M_k}\Gamma_k}\right]^2 \frac{1}{f_s} \tag{8}$$

where f_s is the uniform sample speed. Considering P_{th1} is a constant, the model in (7) can be simplified as

$$\begin{aligned} &\min \quad C(\vec{M},\vec{\Gamma}) = \sum_{k=1}^{U} B_k\theta_k(1-P_{th1})\tau_k \\ &s.t. \quad \sum_{k=1}^{U} M_k = M \end{aligned} \tag{9}$$

The value of M_k and Γ_k in channel k are to be optimized. Actually, it is an assigning problem between the users and the channels. But it is not a linear programming problem. One allocation scheme has an expected cooperative throughput, so if brute force search is adopted, the complexity is $O(U^M)$. Next, we will exploit the feasible algorithms to the allocation.

4. Sensing Task Allocation Algorithms for Heterogeneous Channels

4.1 The Case of Equal Secondary Users

A simple case is that the secondary users are equal, i.e. the received signal from a primary user is the same in the view of different users. This case exists in practice: when the secondary network is far from the primary users, the distance between a certain primary user and each secondary user is almost the same. So we can get:

$$\Gamma_k = \frac{1}{M_k}\sum_{i=1}^{M_k}\eta_k^i = \eta_k^i,$$

for any given M_k. This is to say that the two parameters have been separated. So the target is transformed to

$$\begin{aligned} C(\vec{M},\vec{\Gamma}) &= \sum_{k=1}^{U} B_k\theta_k(1-P_{th1})\tau_k \\ &= \sum_{k=1}^{U} B_k\theta_k(1-P_{th1})\frac{\Psi_k}{M_k f_s} \\ &= C(\vec{M}) \end{aligned} \tag{10}$$

where $\Psi_k = \left[\frac{Q^{-1}(P_{th1})\sqrt{2} - Q^{-1}(1 - \frac{I_{th}}{1-\theta_k})\sqrt{2+4\Gamma_k}}{\Gamma_k}\right]^2$

is already a constant in channel k. Based on this breakthrough, the problem has become a soluble problem.

Considering the discrete variable M_k as a continuous variable, we construct the Lagrangian function as follows.

$$L(\vec{M},\lambda) = C(\vec{M}) + \lambda(\sum_{k=1}^{U} M_k - M) \tag{11}$$

where λ is the Lagrangian coefficient. It is obvious that the function $C(\vec{M})$ is convex and the Lagrangian function satisfies the Karush-Kuhn-Tucker (KKT) conditions [11]. Therefore, it follows that

$$\frac{\partial L(\vec{M},\lambda)}{\partial M_k} = 0, \quad k = 1,2,...,U \tag{12}$$

$$\sum_{k=1}^{U} M_k = M\,. \tag{13}$$

Then the solution is given by

$$M_k = \sqrt{B_k\theta_k(1-P_{th1})\frac{\Psi_k}{f_s\lambda}}, \quad k = 1,2,...,U\,. \tag{14}$$

Constitute (14) into (13), we get

$$\sqrt{\lambda} = \frac{1}{M}\sum_{k=1}^{U}\sqrt{B_k\theta_k(1-P_{th1})\frac{\Psi_k}{f_s}}\,. \tag{15}$$

It follows that

$$M_k = M\sqrt{B_k\theta_k\Psi_k} \Big/ \sum_{k=1}^{U}\sqrt{B_k\theta_k\Psi_k}\ ,\ k=1,2,...,U\ . \quad (16)$$

The value may be not integer, so we round the number to $\lfloor M_k \rfloor$ or $\lceil M_k \rceil$ as a solution. Due to the convexity of the target function, we know that the optimal allocation scheme is in the neighboring set $\{(\delta_1, \delta_2, \ldots, \delta_U) \mid \delta_k = \lfloor M_k \rfloor$ or $\lceil M_k \rceil, \sum_{k=1}^{U}\delta_k = M, k \le U\}$, whose cardinality is smaller than 2^U. Then search the neighboring set to find the optimal scheme. In conclusion, we decrease the complexity from $O(U^M)$ to $O(2^U)$ in this case.

4.2 The Case of Unequal Secondary Users

Generally, the secondary user may not be equal, which means that the heterogeneous geographical positions give different influence to the users. For example, the user with short distance from the primary transmitter may receive higher signal than the one with long distance, so the scenario the two users are treated the same is not appropriate. The whole aim is to gain the expected cooperative throughput maximally, so we propose a suboptimal algorithm, namely, the *two-hierarchy approach algorithm*, as follows. Here, the 'two-hierarchy' means that we complete one match between the secondary users and the channels within selections in two hierarchies. The basic idea in every hierarchy is to seek the most ‘promising’ secondary user or channel.

Note that playing the two-hierarchy selection can only find one match. Once a user is confirmed to sense a certain channel, it quits the selection process. At a given time, we suppose w round selections have been done, i.e. w users has been assigned tasks, $w \le M$. For channel k, $k = 1, 2, \ldots, M$, let $\mathbf{S_k}$ denote the users set having been chosen to sense it. We have

$$\sum_{k=1}^{U}|\mathbf{S_k}| = w \quad (17)$$

where $|\ |$ denotes the cardinality of the set. In addition, we adopt $\mathbf{S_o}$ denoting the set of users that have not been assigned tasks. Before the allocation process, $\mathbf{S_o} = \{1, 2, \ldots, M\}$.

User Hierarchy: The selection in this hierarchy is to select one secondary user for every channel. Note that the selected user is not inevitable to be assigned to sense the channel. For channel k, only the sensing duration could influence the throughput in this given channel. Therefore, we rewrite the expression in (8) here.

$$\tau_k = N_k / f_s = \left[\frac{Q^{-1}(P_{th1})\sqrt{2} - Q^{-1}(1-\frac{I_{th}}{1-\theta_k})\sqrt{2+4\Gamma_k}}{\Gamma_k}\right]^2 \frac{1}{M_k f_s} . \quad (18)$$

From the expression, we know τ_k is inverse proportion to Γ_k. So when $|\mathbf{S_o}|$ must be added to $M_k + 1$, the only thing we can do is to choose the user with the largest received *SNR*, so as to maximize the average global *SNR* Γ_k (meanwhile, minimize the sensing duration τ_k, and maximize the average throughput in channel k). Therefore, the user chosen to try adding to $\mathbf{S_k}$ is shown below.

$$s_k = \arg\max_{i\in\mathbf{S_o}} \eta_k^i, k = 1,2,...,U\ . \quad (19)$$

After all U users are chosen, they are stored in candidate set $\mathbf{S_c} = \{s_k \mid k = 1, 2, \ldots, U\}$, which will be looked up in the next hierarchy. In addition, it is possible that two chosen users are the same secondary user: $s_i = s_j$.

Channel Hierarchy: In this hierarchy, the best candidate user for every channel has been determined. Each adding user would bring reward to the system: increasing the expected throughput in the corresponding channel. In order to gain the most increment in this round, we need to calculate the increment in every channel.

$$\begin{aligned}\Delta_k &= B_k\theta_k(1-P_{th1})(\tau_k - \tau_k^*) \\ &= B_k\theta_k(1-P_{th1})\left(\frac{\psi_k}{|\mathbf{S_k}|} - \frac{\psi_k^*}{|\mathbf{S_k^*}|}\right)\frac{1}{f_s}\end{aligned} \quad (20)$$

where the superscript * means the new parameter, $\mathbf{S^*_k} = \{\mathbf{S_k}, s_k\}$ and

$$\psi_k = \left[\frac{Q^{-1}(P_{th1})\sqrt{2} - Q^{-1}(1-\frac{I_{th}}{1-\theta_k})\sqrt{2+\frac{4}{|\mathbf{S_k}|}\sum_{i\in\mathbf{S_k}}\eta_k^i}}{\frac{1}{|\mathbf{S_k}|}\sum_{i\in\mathbf{S_k}}\eta_k^i}\right]^2 . \quad (21)$$

Then the channel to sense in this round is

$$ch = \arg\max_{k=1,2,...,U} \Delta_k\ . \quad (22)$$

This completes the selection: user s_{ch} is assigned to sense channel ch.

Renew the sets: $\mathbf{S_{ch}} = \{\mathbf{S_{ch}}, s_{ch}\}$, $\mathbf{S_o} = \mathbf{S_o} \backslash s_{ch}$. And then go to the next round until all the secondary users are assigned. The complexity of our algorithm is $O(UM)$ if the complexity of calculating the cooperative sensing duration one time is $O(1)$.

Noticing that the increment in (20) may be negative in some cases, we give detailed explanation in appendix.

5. Performance Simulation

5.1 Near Optimality of the Proposed Algorithms

In this section, we verify our proposed algorithms via simulations. Rectangular coordinates are adopted to measure the geographical position, with the secondary center in its origin. Give the simulation circumstance as follows. The secondary coverage is circularity with the radius 10 km, and the 10 secondary users are randomly distributed in it. Simply, we assume our target channels are two: $B_1 = 3$ MHz, $B_2 = 8$ MHz and $\theta_1 = 0.9293$, $\theta_2 = 0.3500$ (generated by computer). First, we do the experiment in the equal secondary user case, here, the primary users are at (1000 km, 500 km) and (-1000 km, 0 km). Easily, we get the exactly same result to the optimal allocation scheme $M_1 = 5$, $M_2 = 5$, which will not be further discussed here.

Next the two primary users are set at (50 km, 30 km) and (-30 km, 0 km), and $P_{th1} = 0.05$. We simulate the unequal secondary user case. In Fig.4, the small triangle signifies the secondary center, the circularity signifies the users to sense the channel 1, and the square signifies the users to sense the channel 2. We can discover the two different users are only at the interface of the two separated parts. Meanwhile, the expected throughputs in the optimal and actual scheme are almost the same. This means the different users are less important to the whole sensing performance. So the proposed two-hierarchy approach algorithm is nearly optimal.

In addition, from Tab. 1, we can see that though channel 1 is idler than channel 2, the sensing users are not more than those of channel 2. So the allocation is relative to the heterogeneity and the geographical position.

	B_k	θ_k	τ_k	τ_k^{op}	M_k	M_k^{op}	Th_k	Th_k^{op}
Ch1	3MHz	0.9293	0.62ms	0.58ms	4	4	0.0914e6	0.0914e6
Ch2	8MHz	0.35	0.39ms	0.40ms	6	6	0.0890e6	0.0890e6

Tab. 1. The characteristic in two channels (the superscript *op* denotes the optimal allocation, *Th* is the expected throughput in corresponding channel).

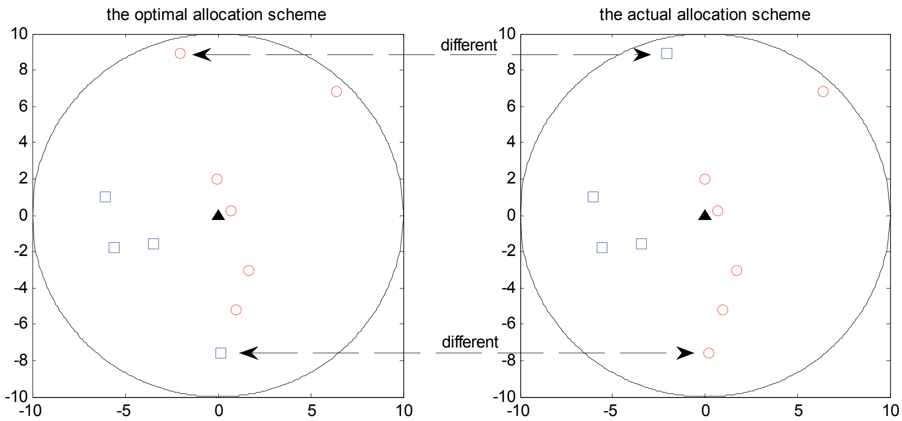

Fig. 4. The comparison between the optimal and the actual allocation schemes.

5.2 Advantage of Sensing Task Allocation

If no sensing task allocation is adopted, every channel must be sensed by all the secondary users before the secondary access. Then the cooperative sensing duration in all channels is the same.

$$\tau = \sum_{k=1}^{U} \frac{N_k}{f_s}$$
$$= \sum_{k=1}^{U} \left[\frac{Q^{-1}(P_{th1})\sqrt{2} - Q^{-1}(1-\frac{I_{th}}{1-\theta_k})\sqrt{2+4\Gamma_k}}{\Gamma_k} \right]^2 \frac{1}{M \cdot f_s} \tag{23}$$

where $\Gamma_k = \frac{1}{M}\sum_{i=1}^{M} \eta_k^i$ is a constant parameter in given circumstance. In this simulation, $I_{th} = 0.01$, and $T = 0.04$ s. We observe the expected cooperative throughput against different M in Fig. 5. The advantage is very obvious giving two P_{th1}. And if there are more channels, the advantage would be larger, in that the sensing duration would be longer in the non-distribution scheme.

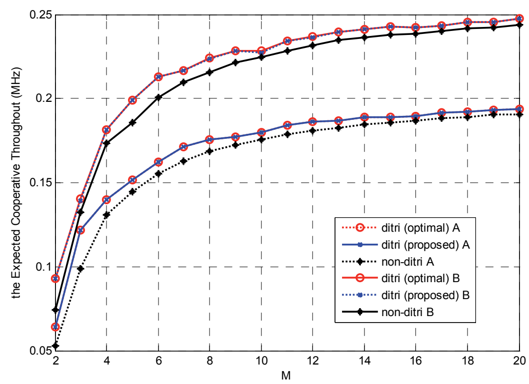

Fig. 5. The systemic cooperative sensing time versus M (A:$P_{th1} = 0.1$, B:$P_{th1} = 0.05$).

As M increases, the sensing task could be done by more 'workers', so the sensing duration in every channel could be cut shorter. But the expected cooperative throughput wouldn't increase endlessly. The ultimate case is that the sensing duration is very very short, i.e. the ultimate expected throughput is

$$Th = \sum_{k=1}^{U} B_k \theta_k (1 - P_{f,k}) T \,. \tag{24}$$

The users in non-task-distributed scheme have to sense all the channels, making the throughput declining. The reason is that the 'worker' (meant for the secondary user) who is not good at the task is allocated to the task, in other word, the sensing resource (here, it is the 'workers') is not optimally allocated.

6. Conclusion and Further Discussions

In this paper, we investigate the cooperative spectrum sensing in multi-primary-user circumstance with heterogeneous channels. Due to the different sensing performance of the same secondary user to different primary users, we propose the sensing task allocation. In order to solve the NP-hard problem, two near optimal algorithms are proposed. After the simulation, we know the advantage of the sensing task distribution and the near optimality of the proposed algorithms.

Three aspects will be in our further research. Firstly, we investigate the soft information in this paper, but in hard information fusion center, the sensing performance is not only related to the center decision but also the local decision. So the hard fusion system needs to be considered again. Secondly, all channels have the same fixed slot duration. Actually, the slot duration is also relative to the interference. So it should be taken into consideration. In addition, the sensing duration and the allocation have to be jointly considered. The last aspect is the consideration of the correctness of local SNR estimation in other fading channel, for example, the Rayleigh fading.

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Appendix

Some Explanations to the Increment Δ_k

In the two-hierarchy approach algorithm, a basic idea is that the sensing duration could be shorten by adding one more sensing user, but actually, from the process, we know $\eta_k^{s_k} \le \Gamma_k$, so

$$\begin{aligned}\Gamma_k^* &= \frac{1}{|\mathbf{S}_\mathbf{k}^*|}\sum_{i\in\mathbf{S}_\mathbf{k}^*}\eta_k^i \\ &= \frac{|\mathbf{S}_\mathbf{k}|}{|\mathbf{S}_\mathbf{k}^*|}\left(\frac{1}{|\mathbf{S}_\mathbf{k}|}\sum_{i\in\mathbf{S}_\mathbf{k}}\eta_k^i\right)+\frac{\eta_k^{s_k}}{|\mathbf{S}_\mathbf{k}^*|} \\ &= \frac{|\mathbf{S}_\mathbf{k}|}{|\mathbf{S}_\mathbf{k}|+1}\Gamma_k+\frac{\eta_k^{s_k}}{|\mathbf{S}_\mathbf{k}|+1}\le\Gamma_k\end{aligned}$$

The decrement

$$\Gamma_k - \Gamma_k^* = \frac{\Gamma_k - \eta_k^{s_k}}{|\mathbf{S}_\mathbf{k}|+1}$$

lies on $|\mathbf{S}_\mathbf{k}|$ and $\eta_k^{s_k}$, and when $|\mathbf{S}_\mathbf{k}| = 1$ and $\eta_k^{s_k} = 0$, the maximal decrement is $\Gamma_k - \Gamma^*_k = \Gamma_k/2$. From (20), if $\psi_k/|\mathbf{S}_\mathbf{k}| \le \psi^*_k/|\mathbf{S}^*_\mathbf{k}|$, then $\Delta_k \le 0$. This case is possible. So the sensing duration for the k^{th} primary user may increase or decrease.

Although the increment Δ_k is negative, the algorithm still stands. Because in the channel hierarchy, the increments in all the channels are to be compared. If the increments are positive, the algorithm stands. If some are positive while the others are negative, the largest in the positive ones will be chosen, in which case the algorithm stands, too. If all the increments are negative, the channel with the least decrement would be chosen. This is reasonable. Actually, this is the fault of equal gain combination. If other combination methods are to adopt, the problem would be solvable.

Next, we give the criteria to judge and avoid the appearance of the problem. We consider the worst case that the number of the sensing users increases from one to two. Without loss of the generality, we assume the local SNR η_k has its own boundaries: $\pi_l < \eta_k < \pi_h$, then the worst value for Γ_k is

$$\Gamma_k = \begin{cases} \pi_h & M_k = 1 \\ \frac{1}{2}(\pi_h + \pi_l) & M_k = 2 \end{cases}$$

We get

$$\begin{aligned}&\tau_k\big|_{M=1} \le \tau_k\big|_{M=2} \\ &\Rightarrow \frac{Q^{-1}(P_{th1}) - \zeta_k\sqrt{1+2\pi_h}}{\pi_h} \le \frac{Q^{-1}(P_{th1})\sqrt{2} - \zeta_k\sqrt{2+2(\pi_h+\pi_l)}}{(\pi_h+\pi_l)}\end{aligned} \tag{*}$$

where $\zeta_k = Q^{-1}\left(1 - \frac{I_{th}}{1-\theta_k}\right)$.

This is to say that, if the inequality (*) could be satisfied, the aforementioned problem could be avoid. This completes the explanation.

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